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SEARCH FOR RADIATIVE DECAYS OF SOLAR NEUTRINOS DURING A SOLAR ECLIPSE

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Abstract

A search for possible radiative decays of solar neutrinos with emission of photons in the visible range may be performed during total solar eclipses. We discuss some results obtained from the digitized images recorded during the August 11, 1999 total solar eclipse in Romania, and report on the observations made in June 21, 2001, in Zambia.

1 Introduction

It is a general opinion that most probably neutrinos have non–zero masses. This belief is based primarely on the evidence/indication for neutrino oscillations from data on solar and atmospheric neutrinos.

Neutrino oscillations are possible if the flavour eigenstates (ν_e, ν_μ, ν_τ) are not pure mass eigenstates (ν_1, ν_2, ν_3), e.g.:

$$|\nu_e >= |\nu_1 > \cos\theta + |\nu_2 > \sin\theta \tag{1}$$

where θ is the mixing angle and $m_{\nu_2} > m_{\nu_1}$.

Since few years there is evidence that the number of solar neutrinos arriving on Earth is considerably smaller than what is expected on the basis of the “Standard

Solar Model" and of the "Standard Model" of particle physics, where neutrinos are massless (see e.g.[1]). One possible explanation of these experimental results involves neutrino oscillations, either in vacuum with $\Delta m^2_{sun} = m^2_{\nu_2} - m^2_{\nu_1} \sim 10^{-10}$ eV^2 (as originally discussed in refs.[2, 3]) or resonant matter oscillations $\Delta m^2_{MSW} \sim 10^{-5}$ eV^2 [4, 5]. Recent results from the Super-Kamiokande,[6] MACRO[7, 8] and Soudan2 [9] experiments on atmospheric neutrinos strongly support the hypothesis of atmospheric neutrino oscillations, in particular $\nu_\mu \rightarrow \nu_\tau$, with large mixing ($\sin^2 2\theta > 0.8$) and $\Delta m^2_{atm} \simeq 2.5 \times 10^{-3}$ eV^2.

Another indication in favor of neutrino oscillations with a third energy scale $\Delta m^2_{LSND} \simeq 1$ eV^2 was reported in ref.[10].

Very recently, the SNO experiment reported evidence of a "non-electron flavor active neutrino component in the solar flux".[11] This implies the observation of solar active ^{8}B neutrinos in close agreement with the predictions of solar models, and thus it is an important result in favor of solar neutrino oscillations.

From the ensamble of data concerning solar and atmospheric neutrinos and considering also the beta spectrum of tritium,[12] the sum of the masses of active neutrinos is estimated to be between 0.05 and 8.4 eV.[11]

The above observations appear to be the first indications for new physics beyond the "Standard Model"; any model that generates neutrino masses must contain a natural mechanism that explains their values and the relation to the masses of their corresponding charged leptons. Different scenarios have been proposed to explain all the observations, including the results with neutrinos from reactors and accelerators.[13, 14, 15]

If neutrinos do have masses, then the heavier neutrinos could decay into the lighter ones. For neutrinos with masses of few eV the only decay modes kinematically allowed are radiative decays of the type $\nu_i \rightarrow \nu_j + \gamma$ (where lepton flavor would be violated). Such decay processes in astrophysics were first suggested by Masiero and Sciama.[16]

Upper bounds on the lifetimes of such decays are based on the astrophysical non–observation of the final state γ rays. Limits were obtained from measurements of X and γ ray fluxes from the Sun[17] and SN 1987A.[18, 19]

In the case of neutrinos with nearly degenerated masses, of the order of the eV, the emitted photon can be in the visible or ultraviolet bands.[20, 21, 22, 23] A first tentative to detect such photons, using the Sun as a source, was made during the total solar eclipse of October 24, 1995.[22]

Direct visible photons from the Sun come at a rate of some 10^{17} cm^{-2} s^{-1}; this makes a direct search for photons from solar neutrino decays impossible. To perform a measurement one must take advantage of a total solar eclipse, which reduces by at least 8 orders of magnitude the direct photon flux. By looking with a telescope at the dark disk of the Moon during a solar eclipse one can search for photons emitted by neutrinos decaying during their 380000 km flight path from the Moon to the Earth.

In this paper we describe the methodology employed for such a search, give limits obtained from a preliminary measurement performed during the total solar eclipse of 11 August, 1999, and we report on the observations made in Zambia, the 21 June, 2001.

2 Kinematics of radiative decays

We assume the existence of a possible neutrino radiative decay, $\nu_2 \to \nu_1 + \gamma$, where $m_{\nu_2} > m_{\nu_1}$; ν_1, ν_2 are neutrino mass eigenstates .

The energy of the emitted photon in the earth reference laboratory system is

$$E_{lab} = E_{cm}\gamma_\nu \left(1 + \beta_\nu \cos\theta^*\right), \tag{2}$$

where E_ν and $\gamma_\nu = \frac{E_\nu}{m_{\nu_2}} = (1-\beta_\nu^2)^{-\frac{1}{2}}$ are in the lab. frame; θ^* and E_{cm} are the photon emission angle with respect to the parent neutrino spin direction, and the energy of the emitted photon in the decaying neutrino rest frame.

For radiative neutrino decays the general expression for the angular distribution of the emitted photons in the rest frame of the parent neutrino is

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 - \alpha\cos\theta^*\right) \tag{3}$$

where the α parameter is equal to -1, +1, for left–handed and right–handed Dirac neutrinos, respectively; it is 0 for Majorana neutrinos.

In order to estimate the expected fraction of photons produced in the visible range and their maximum angle of emission from radiative solar neutrino decays we performed Monte Carlo simulations for neutrino masses in the range $0.1 - 4$ eV and two different sets of oscillation parameters (large mixing: $\Delta m^2 = 2 \times 10^{-4}$ eV^2 and $\sin^2 2\theta = 0.71$; small mixing: $\Delta m^2 = 6 \times 10^{-6}$ eV^2 and $\sin^2 2\theta = 3.98 \times 10^{-3}$), coresponding to the extremes of the Super-Kamiokande allowed regions for MSW oscillations in matter.

Fig: 1 is the result of 5×10^8 simulated radiative decays, for each $(m_{\nu_1}, \Delta m^2)$ set of values, and assuming that neutrinos are left-handed.

3 The August 11, 1999 total solar eclipse

Two experiments were prepared for the observation of solar neutrino radiative decay signatures, during the solar eclipse of August 11, 1999.

The first experiment used a small Cassagrain telescope mounted on an automatic pointing device; the whole apparatus was carried on the rear seat of a MIG-29 supersonic fighter of the Romanian Air Forces, that was supposed to follow the totality of the eclipse in Romania.

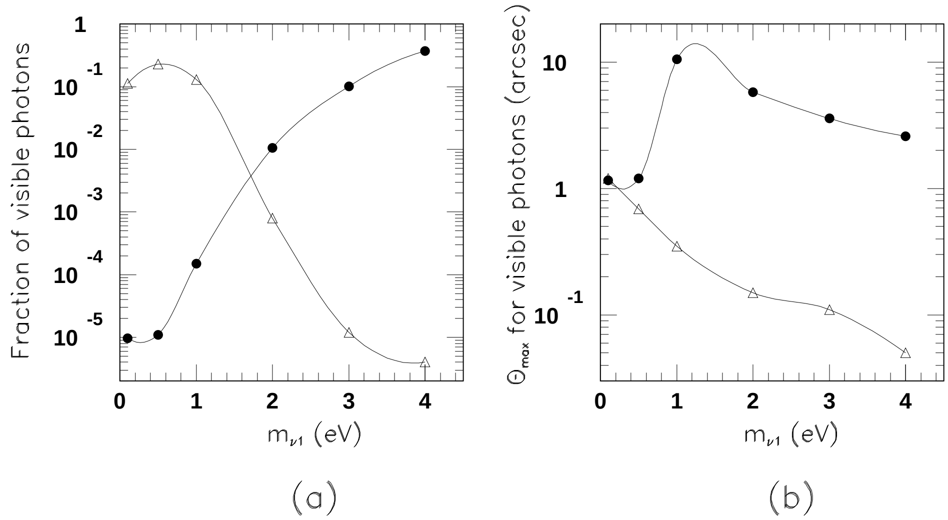

Figure 1: Summary of the Monte Carlo simulations of solar neutrino radiative decays: (a) the fraction of decays leading to visible photons, and (b) the maximum emission angle with respect to the Sun - Earth direction for the visible photons. The black points refer to the ($\Delta m^2 = 2 \times 10^{-4}$ eV^2, $\sin^2 2\theta = 0.71$) oscillation parameters, while the white triangles refer to the ($\Delta m^2 = 6 \times 10^{-6}$ eV^2, $\sin^2 2\theta = 3.98 \times 10^{-3}$) set. The curves are only drown to guide the eye.

A second experiment, used a larger Newtonian telescope, that was supposed to make observations from a site very close to the point of maximum eclipse, in the Parâng Mountains, in South-Western Romania. Both telescopes were equipped with CCD cameras, acquisition and pointing control and recording computers. Combining the results of the two experiments, we expected an improvement of at least a factor of 20 [24] compared to a previous experiment of the same kind.[22]

Unfortunately, both experiments failed due to the extremeley unfavorable weather conditions that made the plane takeoff too hazardous, and the observation from ground impossible.

By the courtesy of the Vâlcea 1 Television in Râmnicu Vâlcea, Romania, we obtained a S-VHS recording of the eclipse, that could be analyzed in a way similar to what we intended to do with the CCD images. The film allowed the analysis in three colours (red, blue and green) and of their sum (white). As no direct calibrations were possible, the numerical results obtained are not accurate, but could still offer a qualitative understanding on the phenomenology under study.

After digitising the film, we selected 2747 good quality frames, each 352×288 pixels^2. For each frame we extracted a 32×32 pixels^2 large square[1], centered on the center of the dark disk of the Moon (which clearly corresponded to the center of the Sun behind) and summed them in a unique "image".

Repeating the same selection on a real full Moon image of the same size, we could

[1]The size of 32×32 pixels^2 is the largest dyadic (integer power of 2) size of a square that fits inside the dark Moon disk.

observe that the structures present in our composed picture were produced by the moonscape seen in the light reflected by the Earth; after suitable normalisations (in intensity and dynamics) we could remove these structures from our data.

In order to make an indirect calibration of our Aquisition Digital Units (ADU's) we used as reference the measurement of the luminosity distribution of the solar corona, made during the same eclipse, by a group of astronomers from the Pises Observatory, France.[26] Using their estimates and the average brightness of the full Moon (0.34 lux, which, assuming an average wavelength of 5500 $\mathring{A}$ corresponds to $\simeq 1.4 \times 10^{11}$ photons $cm^{-2}s^{-1}$ at the earth surface) we could estimate the flux of visible photons that would produce 1 ADU in our image.

Electron neutrinos are produced in termonuclear reactions in a small inner region of the Sun (about 0.6% of the solar diameter corresponding to 12" as seen from the Earth). The decay visible photons are emitted nearly along the direction of incidence of the parent neutrinos; since at our resolution the angular size coresponding to one pixel is about 20", we expect that the decay signal would be present only in the central pixel of the image, or in its adiacent pixels.

We are interested to search for a small effect in the data; thus we applied a wavelet decomposition (see e.g. ref.[25]) of the image, after the removal of the moon background.

The average (over the azimuthal angle) residual light fluxes corresponding to the fourth order residual in the wavelet decomposition, are presented in Fig: 2, for the red, blue, green and white light. Note that the negative flux values at some distances from the center are an artefact due to the wavelet analysis of noisy signals, and indicate the degree of fluctuations in our measurement.

It should be mentioned that the videocamera produces the green channel by subtracting the red and the blue channels from the image obtained without filters (white); thus the green channel is somewhat artificial.

After the digitization of the video recording, we reconstructed the white channel as the sum of the blue, red and the fake green channels. We checked the consistency of the peaks corresponding to the central pixels in the four color channels (see Fig: 2) by repeating the analysis considering other pixels of the image as "central". In these cases we did not obtain the same structures as in Fig: 2.

We tried to explain the peaks at small angular distances assuming that the central maxima are due to some diffraction pattern. In the particular case of a circular opaque object (in our case the Moon) whose size is much larger than the wavelength of the light emitted by the source (the Sun), but much smaller than the distance from the object to the source to the screen (detector), an "unusual" diffraction effect known as "the Poisson spot" occurs.[27, 28, 29] It consists in a strong diffraction maximum at the center of the shadow of the circular object; for point sources its intensity should be the same as if the circular obstacle was not there; for plane waves it should be a quarter of this. The Moon is not a perfect circular obstacle and the Sun is neither a

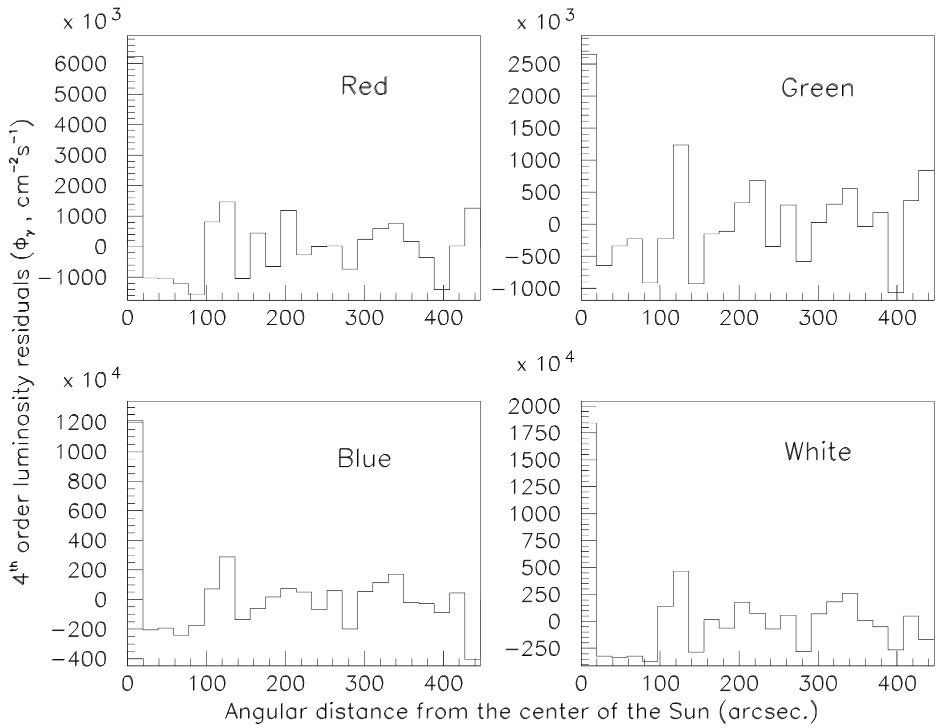

Figure 2: Average residual light fluxes, after Moon substraction and wavelet decomposition, in the red, green, blue channels and summed (white), as a function of the angular distance from the center of the Moon disk.

point source of light, nor a source of plane waves, furthermore the apparent angular dimension of the solar corona is larger than that of the Moon, thus we are not in the ideal case of the production of the Poisson spot; on the other hand, the distance conditions are fully fullfiled in the case of a total solar eclipse seen from Earth (the town of Râmnicu Vâlcea was only few km from the point of maximum eclipse), so we could expect that such a diffraction effect is present in our data.

In the diffraction hypothesis, the intensity of the central diffraction maximum should not be dependent on the wavelength; thus the ratios between the intensity of the signal due to diffraction in the central pixel of our image should be the same as in the case of a solar spectrum recorded with a similar video camera. Using such a recording and assuming that all the signal in the red channel is due to the Poisson spot, we obtained an excess of few percent in the blue and white lights.

Once the residual flux of photons corresponding to the central pixel Φ_γ is determined, the lifetime τ of the ν_2 neutrino with respect to its radiative decay (in the earth reference system) could be computed from:

$$\Phi_\gamma = \epsilon \Phi_\nu \sin^2\theta \left(1 - e^{\frac{t_{M\to E}}{\tau}}\right) e^{\frac{t_{S\to M}}{\tau}}. \tag{4}$$

Here ϵ is the fraction of visible photons produced trough the radiative decay of neutrinos, $\Phi_\nu \sin^2\theta$ represents the component ν_2 of the expected solar neutrino flux at the earth location; $t_{S\to M}$ and $t_{M\to E}$ are the average times of flight of the ν_2 neutrinos from the Sun to the Moon and from the Moon to the Earth, respectively.

By solving Eq. 4 for different choices of the oscillation parameters (as shown in Fig: 1) we obtained limits on the ν_2 lifetime of the order of 10^6s (in the earth reference frame).

As already stressed, our indirect calibration has large uncertainties (estimated to be at the level of 25% in terms of the photon flux); thus the above result represents more an estimate of the achieved sensitivity than an actual limit.

4 The June 21, 2001, total solar eclipse

The total solar eclipse of June 21, 2001, that crossed Southern Africa, allowed us to repeat the experiment. This time we performed only ground observations, from a location $14°56'$ lat. S, $28°14'$ long. E. This location was at an altitude of about 1200 m a.s.l., at approximately 8 km from the central line of totality, and at about 50 km North of Lusaka, Zambia. From this location we could observe the totality for about 3.5 minutes.

We used two small Matsukov Cassagrain telescopes and a digital video-camera.

a) One of the Cassagrain telescopes (with a 12.5 cm aperture) was equipped with a web-camera (and a small TV camera for pointing purposes). The recorded data consist in a digital film of the central part of the dark side of the Moon (about 3000 single frames, each with an exposure time of 1/25 s)

b) The second Cassagrain (9 cm of aperture) had a digital photo-camera that recorded 12 high resolution (1600×1280 pixels^2) digital photographs, integrating 24 s of exposure. We took care to slightly change each time the field of view in order to prevent some possible spurious reflection effects.

c) The digital video-camera was equipped with a ($2\times$) telelens and a $10\times$ optical zoom; it produced a digital recording equivalent to about 8000 single frames.

The quality of all images seems good and we should have avoided the drawbacks reported in Section 3. The data obtained by the three methods are currently under analysis; preliminary results seem to support the conclusions from the 1999 eclipse.

5 Conclusions

During the 1999 and 2001 total solar eclipses we looked for possible solar neutrino decays, which lead to an optical signature (visible light).

The analysis of the data extracted from the television recording of the 1999 total solar eclipse is essentially completed. Some conclusions could be drawn.

a) An important surce of background was identified as the moonscape seen in the light reflected by the Earth.

b) After removing the moon image and applying a wavelet decomposition to the data, a peak remained, in all the color channels at a small angular distance from the center of the Moon (Sun); the peak could be produced by the diffraction mechanism known as the "Poisson spot"; also with this assumption we could not completely remove the signal.

c) The estimated sensitivity of our analysis in terms of the ν_2 lifetime is about 10^6s (in the earth reference system).

The 2001 data were collected in good meteorological conditions, with three different instruments with different resolutions, duty cicles and magnifications. Preliminary analyses of subsets of the data indicate much better quality data. The analyses of the bulk of the data and the calibrations of the equipments are in progress. We expect to obtain an improvement of at least one order of magnitude with respect to the 1999 results.

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